# UTILITY PATENT APPLICATION TRANSMITTAL (Small Entity) *(Only for new nonprovisional applications under 37 CFR 1.53(b))*	Docket No. IRV-104.1
	Total Pages in this Submission

TO THE ASSISTANT COMMISSIONER FOR PATENTS
Box Patent Application
Washington, D.C. 20231

Transmitted herewith for filing under 35 U.S.C. 111(a) and 37 C.F.R. 1.53(b) is a new utility patent application for an invention entitled:

SHORT PULSE MID-INFRARED PARAMETRIC GENERATOR FOR SURGERY

and invented by:

William B. TELFAIR, et al.

If a **CONTINUATION APPLICATION,** *check appropriate box and supply the requisite information:*

☐ **Continuation** ☒ **Divisional** ☐ **Continuation-in-part (CIP)** of prior application No.: 08/816,097

Which is a:

☐ **Continuation** ☐ **Divisional** ☒ **Continuation-in-part (CIP)** of prior application No.: 08/549,385

Which is a:

☐ **Continuation** ☐ **Divisional** ☐ **Continuation-in-part (CIP)** of prior application No.: _____

Enclosed are:

Application Elements

1. ☒ Filing fee as calculated and transmitted as described below

2. ☒ Specification having _____32_____ pages and including the following:

    a. ☒ Descriptive Title of the Invention

    b. ☒ Cross References to Related Applications *(if applicable)*

    c. ☐ Statement Regarding Federally-sponsored Research/Development *(if applicable)*

    d. ☐ Reference to Microfiche Appendix *(if applicable)*

    e. ☒ Background of the Invention

    f. ☒ Brief Summary of the Invention

    g. ☒ Brief Description of the Drawings *(if drawings filed)*

    h. ☒ Detailed Description

    i. ☒ Claim(s) as Classified Below

    j. ☒ Abstract of the Disclosure

UTILITY PATENT APPLICATION TRANSMITTAL (Small Entity) *(Only for new nonprovisional applications under 37 CFR 1.53(b))*	Docket No. IRV-104.1
	Total Pages in this Submission

Application Elements (Continued)

3. ☐ Drawing(s) *(when necessary as prescribed by 35 USC 113)*

    a. ☐   Formal   b. ☐   Informal   Number of Sheets _____

4. ☒ Oath or Declaration

    a. ☐   Newly executed *(original or copy)*   ☐   Unexecuted

    b. ☒   Copy from a prior application (37 CFR 1.63(d)) *(for continuation/divisional application only)*

    c. ☒   With Power of Attorney   ☐   Without Power of Attorney

    d. ☐   *DELETION OF INVENTOR(S)*
         Signed statement attached deleting inventor(s) named in the prior application,
         see 37 C.F.R. 1.63(d)(2) and 1.33(b).

5. ☒ Incorporation By Reference *(usable if Box 4b is checked)*
The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied under Box 4b, is considered as being part of the disclosure of the accompanying application and is hereby incorporated by reference therein.

6. ☐ Computer Program in Microfiche

7. ☐ Genetic Sequence Submission *(if applicable, all must be included)*

    a. ☐   Paper Copy

    b. ☐   Computer Readable Copy

    c. ☐   Statement Verifying Identical Paper and Computer Readable Copy

Accompanying Application Parts

8. ☐ Assignment Papers *(cover sheet & documents)*

9. ☐ 37 CFR 3.73(b) Statement *(when there is an assignee)*

10. ☐ English Translation Document *(if applicable)*

11. ☐ Information Disclosure Statement/PTO-1449   ☐ Copies of IDS Citations

12. ☒ Preliminary Amendment

13. ☒ Acknowledgment postcard

14. ☒ Certificate of Mailing

    ☐   First Class   ☒   Express Mail *(Specify Label No.):* **EL088351392US**

         P01USML/REV03

UTILITY PATENT APPLICATION TRANSMITTAL
(Small Entity)
(Only for new nonprovisional applications under 37 CFR 1.53(b))

Docket No.
IRV-104.1
Total Pages in this Submission

Accompanying Application Parts (Continued)

15. ☐ Certified Copy of Priority Document(s) *(if foreign priority is claimed)*

16. ☐ Small Entity Statement(s) - Specify Number of Statements Submitted: _____

17. ☐ Additional Enclosures *(please identify below):*

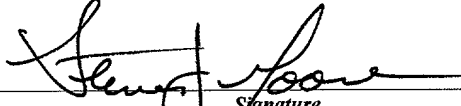## Fee Calculation and Transmittal

CLAIMS AS FILED

For	#Filed	#Allowed	#Extra	Rate		Fee
Total Claims	26	- 20 =	6	x	$9.00	$54.00
Indep. Claims	2	- 3 =	0	x	$39.00	$0.00
Multiple Dependent Claims (check if applicable) ☐						$0.00
					BASIC FEE	$380.00
OTHER FEE *(specify purpose)*						$0.00
					TOTAL FILING FEE	$434.00

☒ A check in the amount of   **$434.00**   to cover the filing fee is enclosed.

☒ The Commissioner is hereby authorized to charge and credit Deposit Account No.   **11-0231**
as described below. A duplicate copy of this sheet is enclosed.
- ☐ Charge the amount of   as filing fee.
- ☒ Credit any overpayment.
- ☒ Charge any additional filing fees required under 37 C.F.R. 1.16 and 1.17.
- ☐ Charge the issue fee set in 37 C.F.R. 1.18 at the mailing of the Notice of Allowance,
  pursuant to 37 C.F.R. 1.311(b).

Dated: *May 10, 1999*

_____
Signature

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Telephone: (203) 351-4333

CC:

P01USML/REV03

VERIFIED STATEMENT (DECLARATION) CLAIMING SMALL ENTITY STATUS (37 CFR 1.9(f) and 1.27(c)) - SMALL BUSINESS CONCERN

I hereby declare that I am

☐ the owner of the small business concern identified below:

☒ an official of the small business concern empowered to act on behalf of the concern identified below:

NAME OF CONCERN   IR Vision, Inc.

ADDRESS OF CONCERN   3997 Starview Drive
San Jose, CA 95124

I hereby declare that the above identified small business concern qualifies as a small business concern as defined in 13 CFR 121.3-18, and reproduced in 37 CFR 1.9 (d), for purposes of paying reduced fees under section 41(a) and (b) of Title 35, United States Code, in that the number of employees of the concern, including those of its affiliates, does not exceed 500 persons. For purposes of this statement, (1) the number of employees of the business concern is the average over the previous fiscal year of the concern of the persons employed on a full-time, part-time or temporary basis during each of the pay periods of the fiscal year, and (2) concerns are affiliates of each other when either, directly or indirectly, one concern controls or has the power to control the other, or a third party or parties controls or has the power to control both.

I hereby declare that rights under contract or law have been conveyed to and remain with the small business concern identified above with regard to the invention, entitled by inventor(s) described in

☐ the specification filed herewith

☒ application serial no.   08/549,385   , filed   10/27/95

☐ patent no.   , issued

If the rights held by the above identified small business concern are not exclusive, each individual, concern or organization having rights to the invention is listed below* and no rights to the invention are held by any person, other than the inventor, who could not qualify as a small business concern under 37 CFR 1.9 (d) or by any concern which would not qualify as a small business concern under 37 CFR 1.9 (d) or a nonprofit organization under 37 CFR 1.9 (e).

*NOTE: Separate verified statements are required from each named person, concern or organization having rights to the invention averring to their status as small entities. (37 CFR 1.27)

NAME
ADDRESS
☐ INDIVIDUAL   ☐ SMALL BUSINESS CONCERN   ☐ NONPROFIT ORGANIZATION

NAME
ADDRESS
☐ INDIVIDUAL   ☐ SMALL BUSINESS CONCERN   ☐ NONPROFIT ORGANIZATION

I acknowledge the duty to file, in this application or patent, notification of any change in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or any maintenance fee due after the date on which status as a small entity is no longer appropriate. (37 CFR 1.28 (b))

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application, any patent issuing thereon, or any patent to which this verified statement is directed.

NAME OF PERSON SIGNING   William B. Telfair
TITLE OF PERSON OTHER THAN OWNER   President
ADDRESS OF PERSON SIGNING   3997 Starview Dr., San Jose, CA 95124

SIGNATURE _____   DATE 1/29/96

S1989941.DOC 01/25/96

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PATENT

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicants:	Telfair et al.	**Art Unit:**	Not Assigned (Parent Application: 3736)
Serial No.:	Not Assigned (Divisional of U.S. Appl. No.: 08/816,097)	**Examiner:**	Not Assigned (Parent Application: Shay, D.)
Filing Date:	See Express Mail Label (Claiming Priority to March 14, 1997)	**Docket No.:**	483540.0015 (IRV-104.1)
Title:	SHORT PULSE MID-INFRARED PARAMETRIC GENERATOR FOR SURGERY		

BOX PATENT APPLICATION
Assistant Commissioner for Patents
Washington, DC 20231

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PRELIMINARY AMENDMENT

</div>

Dear Sir:

Prior to examination of the application filed concurrently herewith, and before calculation of the fee, Applicant submits the following Preliminary Amendment to place the instant application in better condition for examination on the merits:
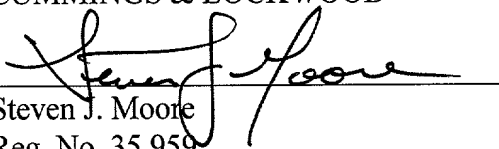
IN THE CLAIMS

- Please Cancel Claims 1 - 16, 30 - 31, and 45 - 59, which are being prosecuted in the parent application hereto. Claims 17 - 29 and 32 - 44 are the only claims pending in the instant application and presented for consideration.

Applicants aver that no new matter has been added.

Respectfully submitted,

CUMMINGS & LOCKWOOD

Dated: May _10_, 1999

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S5150841.DOC 05/07/99

SHORT PULSE MID-INFRARED
PARAMETRIC GENERATOR FOR SURGERY

This application is a continuation-in-part of patent application Serial No. 08/549,385, filed October 27, 1995.

BACKGROUND OF THE INVENTION

In recent years, photorefractive keratectomy (PRK) techniques for reshaping the cornea of the eye have become widely utilized as an effective means for correcting visual deficiencies. These methods are generally based on volumetric removal of tissue using ultraviolet (UV) radiation, typically from a 193 nm ArF excimer laser. At this short wavelength, the high photon energy causes direct breaking of intramolecular bonds, in a process known as photochemical decomposition. Tissue ablation based on this photochemical mechanism has the advantage of producing minimal collateral thermal damage in cells adjacent to the surgical site. Also, the depth of decomposition is very small, typically less than 1 micron, resulting in accurate tissue removal with minimal risk of damage to underlying structures from UV radiation.

While excimer-based methods have been established as a safe and effective method of corneal ablation, they suffer from a number of deficiencies, including high initial cost and ongoing maintenance costs, large and complex optical beam delivery systems, safety hazards due to the fluorine and ozone gas formation and persistent reliability problems. Furthermore, the potential phototoxicity of high-power UV radiation is still an undetermined risk in excimer-laser-based PRK. In particular, there is concern that the UV radiation poses certain mutagenic and cataractogenic risks due to secondary fluorescence effects.

A recently suggested alternative to the excimer laser for performing corneal refractive surgery involves ablation at mid-infrared wavelengths using, in particular, radiation around 3 μm corresponding to the absorption peak of water, the main constituent of the cornea. The premise underlying interest in such an alternative system is that infrared radiation can be produced with solid-state technology, which would provide easier handling, is cheaper, more compact and has better reliability features while eliminating the potential of any safety concerns due to toxic gases or mutagenic side effects associated with UV wavelengths. One solid state laser in particular, the erbium:YAG (Er:YAG) laser, emits radiation at a wavelength of 2.94 μm, corresponding to an absorption coefficient of over 13000 cm -1 in water. This high absorption results in a relatively small region of impact with potentially less than 2 microns penetration depth. Contrary to the photoablation mechanism associated with the excimer laser, i.e., photochemical decomposition, ablation at the erbium wavelength is attributed to photovaporization, or photothermal evaporation, of water molecules. This process is inherently more efficient than photodecomposition, allowing for removal of up to 3 microns of tissue at a time, resulting in faster surgical operation. Such a system has been suggested for example by T. Seiler and J. Wollensak, "Fundamental Mode Photoablation of the Cornea for Myopic Correction", Lasers and Light in Ophthalmology, 5, 4, 199-203 (1993). Another system has been described by Cozean et al. in PCT Application No. 93/14817, which relies on a sculpting filter to control the amount of tissue removal using a pulsed 3 μm Er:YAG laser. However, while ophthalmic surgical techniques based on free running or long-pulse erbium lasers have shown some promise, they also suffer from a number of drawbacks principally relating to the fact that the IR radiation causes collateral thermal damage to tissue adjacent to the ablated region, where the size of the damage zone may exceed several microns, resulting in potentially undesirable long term effects.

Recently, it has been recognized that lasers having a pulse duration shorter than a few tens of nanoseconds will demonstrate less dominant thermal effects. In particular, a direct tissue interaction effect known as photospallation has been observed at infrared wavelengths whereby, with shorter pulses, radiation interacts exclusively with the irradiated tissue producing negligible effect upon the adjacent, unirradiated tissue. Photospallation is a photomechanical ablation mechanism which results from the rapid absorption of incident radiation and subsequent expansion by the corneal tissue. This expansion is followed by a bi-polar shock wave that causes removal of tissue. For a detailed description of a method and apparatus for performing corneal surgery that directly exploits the photospallation mechanism to remove tissue, see U.S. Patent Application Serial No. 08/549,385, the parent application to the present invention, which is incorporated by reference herein. The method and apparatus disclosed therein utilize a short-pulse (preferably less than 50 ns) solid state laser emitting mid-infrared radiation, preferably at or around 2.94 µm, scanned over a region of the cornea to allow uniform irradiation of the treatment region using a relatively low-energy laser. As pointed out in the parent application, a desired laser source for this application would have output energy of up to 30 mJ and repetition rates of up to 100 Hz, depending on the details of the delivery system.

An erbium-doped laser operating at 2.94 µm is one option for such a laser source. A compact, reliable Q-switched erbium laser is described in our co-pending patent application Serial No. 08/549,385. While highly attractive because of its simplicity, even with the aid of future diode pumping, it may be difficult to extend the erbium laser operation to high repetition frequencies (in excess of 30 Hz) due to strong thermal birefringence effects. Limitations of the fundamental level dynamics and long upper-laser-level lifetimes may also conspire with peak-power damage to optical component coatings

to impose a practical lower limit on the pulse duration of 20 ns or so in an erbium-based laser operating in a Q-switched mode.

Recognizing that it is possible that a shorter pulse (less than 20 ns) may increase the percentage of true photospallative ablation process, and thus further reducing residual contributions to tissue ablation from undesirable thermal effects, it is desirable to construct the shortest pulse solid state mid-infrared laser source that can safely and efficaciously meet the requirements of PRK. Ideally, such a source would also be scalable to high repetition frequencies (approaching 100 Hz) without substantially increasing the expense and complexity of the device or compromising its reliability.

An Optical Parametric Oscillator (OPO) that can downshift the frequency of radiation from a standard neodymium-doped laser, such as Nd:YAG, operating at or about 1.06 μm has been suggested as an alternative approach in our co-pending U.S. patent application Serial No. 08/549,385, to obtaining the desired parameters at mid-IR wavelengths. However, no such device has been available to date that can meet all the requirements of the ophthalmic surgical procedures contemplated. For example, efficient OPOs which are pumped by a 1 micron laser with output in the IR range have been demonstrated in recent years using a number of different nonlinear crystals such as Lithium Niobate (LiNbO$_3$) and Potassium Titanyl Phosphate (KTiOPO$_4$ or "KTP"). Examples of parametric oscillation near the 3 μm wavelength of interest include the generation of high-power radiation (8W) at 3.5 μm using LiNbO$_3$ pumped by a 100 Hz, single-mode pump beam (see A. Englander and R. Lavi, OSA Proceedings on Advanced Solid-State Lasers, Memphis, Tennessee, 1995, p. 163) and demonstration of a 0.2W output at 3.2 μm using KTP in a non-critical phase match configuration (see, for example, K. Kato in IEEE J. Quantum Electronics. 27, 1137 (1991)). Realization of an optical parametric device with output at the desired 2.9 to 3.0 μm wavelength range was considered difficult because the two readily available candidate crystals of LiNbO$_3$ and KTP exhibit absorption in that

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wavelength range. Use of LiNbO$_3$ in particular is not considered feasible because of absorption at or near 3.0 μm due to the OH-band present in the crystal using current growth methods. Other drawbacks of the OPO design include a perceived requirement for powerful and high-beam-quality pump sources that can overcome the high threshold for the onset of a parametric process. Since the effectiveness of increasing the pump power density by focusing the pump beam is limited by the walk-off angle of the nonlinear crystal, the threshold condition cannot be overcome simply by using small pump beam diameters in most crystals. A way to circumvent this problem is to use a crystal that can be non-critically phase-matched (such as KTP), resulting in higher acceptance angles, but this configuration is not possible for a 1 μm pump beam wavelength and with the output wavelength desired for a successful PRK procedure. Non-critical phase-matching with output in the 2.9-3.0 μm range is, however, feasible in KTP (x-cut) pumped at 0.88 to 0.9 μm. Lasers emitting at this wavelength range are, however, more complex and expensive than standard neodymium doped laser at or near 1 micron.

For a medical laser instrument, it is generally not desirable to impose overly stringent requirements on the pump laser, as that would result in more complex and costly systems. Ideally, a multimode gaussian or a top-hat beam profile that is commercially available would be desired. However, prior to the present invention, it was not clear that such a pump beam, which can possess substantial divergence, would produce the requisite output energies without damaging the OPO crystal and/or the coupling optics. Also, in the case of a gaussian spatial profile beam, uneven distribution of the peak power density across the crystal can result in only part of the beam contributing significantly to the parametric generation thereby compromising the efficiency of conversion. Furthermore, absorption in KTP, which is known to be substantial at 3.0 μm, was another issue of concern especially for operation at elevated average power levels and/or high repetition

rates. These as well as other reasons prevented the realization to date of an OPO source of pulsed 2.9-3.0 μm radiation of practical output energies and repetition rates.

The present invention discloses a specific apparatus for producing short-pulse radiation at or near 2.94 μm which overcomes the aforementioned difficulties. The apparatus is uniquely suited to performing PRK and other microsurgery procedures at minimal complexity and low cost, thus greatly increasing the availability of such procedures to a large number of people. Furthermore, with certain adjustments to the apparatus, it may be used for certain other ophthalmic procedures where a concentrated pulsed beam at a selected mid-IR wavelength has demonstrated benefits. These procedures include laser sclerostomy, trabeculectomy and surgery of the vitreous and /or the retina. In these procedures means for affecting precise, highly localized tissue ablation are desired. For example, in the case of laser-assisted vitroretinal surgery, the application of mid-IR radiation at 2.94 μm offers the potential of tractionless maneuvers, shallow penetration depths and extreme precision both in transecting vitreous membranes and in ablating requisite epiretinal tissue. See, for example, J.F. Berger, et al. in SPIE, vol. 2673, 1994, p. 146. Furthermore, by utilizing short pulses as disclosed in the present invention, the procedure may be efficaciously conducted at lower fluence levels thus easing requirements on probe geometry. In glaucoma filtration procedures such as ab externo sclerostomy, where a fistula is created from the anterior chamber of the eye into the subconjuctival space, the application of a nanosecond, low energy pulses from an excimer laser at 308 mm proved highly advantageous in treating a number of severely affected patients. See, for example, J. Kampmeier et al. in Ophthalmolge, 90, p. 35-39, 1993. Similar effectiveness of the procedure is expected for mid-IR wavelength due to the high absorption properties of the sclera. The main issue which prevented wider use to date of mid-IR laser radiation in micro-ocular surgery was the lack of a suitable fiber for delivering the energy to the target tissue. However, recent developments in this area culminated in a number of

potential fiber technologies including zirconium fluoride, sapphire silver halide and hollow

waveguide technologies. With further improvements in damage thresholds, it appears that

sufficiently flexible, low loss fibers and appropriate probes may become available in the

very near-term that can handle delivery of even short pulse, 3-micron radiation, for lower

energy (<20 mJ) applications. The emergence of such fiber delivery systems may also

make short pulse, mid-IR radiation highly attractive in general endoscopic microsurgery.

In particular, medical procedures such as brain, orthoscopic and spinal cord surgery may

benefit from the highly localized effects generated by the photo-mechanical ablation

associated with the present system because the delicate nature of the tissues involved

places a premium on limiting collateral thermal injury in surrounding tissue. Of course,

optimal parameters of the laser may very with the application, tissue type and desired

effect. But in this respect, the OPO laser has an advantage in that it offers great flexibility

in terms of available outputs including variations in wavelength and pulse duration.

SUMMARY OF THE INVENTION

It is therefore an object of this invention to provide a new and improved

surgical apparatus, that is particularly adapted for performing corneal refractive surgery. It

is another object to facilitate a new and improved method of photorefractive laser surgery

based on utilizing short-pulse, mid-infrared radiation produced by parametric down-

conversion of radiation from a neodymium-doped laser, such as Nd:YAG.

The short pulses are viewed as critical to reducing unwanted changes in

adjacent tissue and especially thermal effects which can result in undesirable irregular

edges of the interaction site produced by the infrared radiation. With sufficiently short

pulses, the thermal damage can be reduced to potentially sub-micron levels, resulting in the

same clinical indications as ablative photodecomposition produced by deep-UV lasers,

commonly used in refractive surgical procedures. Consequently, it is a key aspect of the

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present invention to provide a laser source with pulse durations shorter than 25 ns at or near 3.0 μm but preferably close to the 2.94 μm water absorption maximum.

It is a further object of this invention to provide a new and improved laser surgical apparatus utilizing an OPO based on a nonlinear crystal such as KTP or its isomorphs for shifting the wavelength of a neodymium-doped laser to the desired mid-infrared wavelength range near 3.0 μm. In an alternative embodiment, a related objective would be to provide a non-critically phased-matched crystal to shift the wavelength from a near-infrared laser source emitting at or around 880-900 nm to the desired 3.0 μm wavelength range.

In yet another object, the OPO cavity parameters are such as to accommodate a readily available pump beam of moderate power while still producing a stable output with pulse energies scalable to the tens of millijoules level. In a preferred embodiment of the OPO laser, pump beams that are single or multi-mode with either gaussian or top-hat spatial profiles and with divergence ranging to many times the diffraction limit would all be accommodated, while maintaining a simple optical configuration with a minimum number of elements.

It is a further object to provide, within the OPO configuration, means for elevating damage thresholds, such that short pulse pump beams with energy outputs over 200 mJ at wavelengths at or near 1-micron can all be accommodated without damage at repetition rates exceeding 10 Hz and preferably approaching 50 Hz. A related object is to provide optimal OPO configurations such that the lowest pump thresholds result for a desired output in the mid-IR range.

It is still another object to provide a new apparatus and method for performing refractive surgery using a fiber or a fiber bundle or some other waveguide means to separate the pump laser from the OPO cavity. The OPO portion could then be

mounted to the surgical microscope providing the surgeon with maximal flexibility for delivering the light to the patient's eye.

A more complete understanding of the present invention, as well as further features and advantages of the invention, will be obtained by reference to the detailed description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram illustrating a preferred embodiment of the OPO laser device according to the present invention.

Figure 2 is a schematic diagram illustrating an alternative embodiment of the OPO laser source, using an L-shaped configuration.

Figure 3 is a schematic diagram illustrating another alternative embodiment of the OPO using a single-pass pump beam.

Figure 4 is a schematic diagram illustrating yet another alternative embodiment using single-pass pump beams in a ring configuration.

Figure 5 is a schematic diagram illustrating of a preferred embodiment of the OPO laser source where the pump beam is fiber coupled to the OPO.

DETAILED DESCRIPTION

A mid-IR laser source is disclosed with parameters selected to yield a beam with properties matched to optimal tissue removal based on a photospallation mechanism. Optimally, the laser beam comprises a series of discrete pulses of less than 25 ns in duration, each with energy of greater than 1 mJ emitted at repetition rates of at least 10 Hz, but scalable to over 50 Hz. High repetition rate is required to minimize the duration of the medical procedure while allowing small spot sizes with better overlap parameters to be utilized for improved surgical outcomes. The critical nature of the pulse duration is related

to the threshold for the photospallation process, which is expected to be lower as the pulse duration decreases thus allowing for lower energy densities (or, fluences) to be utilized to affect ablation. Generally, the lower the energy density, the less likely it is that thermal damage to tissue surrounding the ablation site will occur. This, in turn, is an important factor in producing highly localized ablation with clinical results similar to what is obtained currently with UV radiation.

As shown in Fig. 1, a mid-infrared laser source 1 preferably includes a neodymium-doped laser source pump 20, generating a pump beam 50 comprised of short laser pulses (preferably less than 30 ns) at or around 1 micron, which radiation is down-converted to the mid-IR wavelength range through an Optical Parametric Oscillator (OPO) 10. The OPO 10 is shown to include mirrors 12, 16 and a nonlinear crystal 15. The effect of the nonlinear crystal 15 on the laser pulses results in two beams, in a known manner. Specifically, the output of the OPO comprises an idler beam 52 and a signal beam 54. For a detailed description of the operation of one particular OPO, see U.S. Patent No. 5,181,211, incorporated by reference herein.

For refractive surgery, the desired wavelengths are those of the idler beam 52, which in the preferred embodiment fall in the range between 2.89 and 2.98 μm. In the example of a Nd:YAG pump beam at 1.064 μm, the corresponding wavelength of the signal beam 54 is between 1.68 and 1.66 μm. It is to be understood, however, that while a wavelength near the 2.94 μm water absorption peak is preferred, especially for PRK applications, idler wavelengths anywhere in the range of approximately 2.75 to just over 3.0 μm fall within the scope of the invention, with the specific wavelength chosen to match the needs of the surgical application.

The idler beam 52 is reflected from dichroic beam splitter 35 and is subsequently directed to beam transfer optics 40, which, in a preferred embodiment may include imaging and scanner means to allow selective removal of tissue at various points

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on the cornea, thereby causing the cornea to change in a predictable and controlled manner. Such means were disclosed in our co-pending parent application, U.S. Serial No. 08/549,385, incorporated herein by reference, and are not considered critical to the present invention. The signal beam 54 is transmitted through the beam splitter 35 to a beam dump 32. Further attenuation of the residual signal beam 54 may be provided by additional reflectors collectively represented as attenuator 34 which may be placed in the path of the idler beam 52 to prevent any coupling of the signal wavelengths from the signal beam 54 into the delivery system 40.

In the embodiment of Fig. 1, the coatings and positioning of the mirrors 12, the crystal 15 and the mirror 16 in the OPO cavity 10 are chosen to comprise a singly resonant oscillator (SRO) configuration optimized for producing the idler wavelengths and with the added feature of using backreflection of the unconverted portion of the pump beam 50 into the crystal for further processing. Thus, mirror 12 is coated for high transmission of wavelengths between 1.0 and 1.1 μm and high reflection of the idler wavelengths between 2.8 and 3.0 μm. Mirror 16 is coated to have partial reflectance for wavelengths between 2.8 and 3.0 μm and high transmission at the 1.65 to 1.7 μm wavelengths characteristic of the signal beam 54. The signal beam 54 thus passes through the oscillator cavity without reflection, while the idler beam 52 is resonated to assure maximum output at the mid-IR wavelengths. Preferably, mirror 16 is also coated for high reflectance at the pump wavelengths between 1.0 and 1.1 μm. It is not, however, essential to provide this last high reflectance but such reflection may be advantageous for more efficient operation of the device by lowering the energy threshold for the parametric process.

An alternative configuration to the SRO is that of a Doubly Resonant Oscillation (DRO), where both the idler and signal waves are resonated. In general, a DRO is known to have a lower oscillation threshold but has the drawback of more complicated

mirror coatings, and somewhat more difficult alignment procedures. Nonetheless, while an SRO is preferred due to greater simplicity and lower cost of components, DRO configurations are considered an alternative embodiment for cases where a substantially reduced oscillation threshold presents an advantage. It should be noted that while DRO outputs are known to be less stable than those of an SRO, this is not an issue for this present application where only pump beams comprising a multiplicity of longitudinal modes are utilized. A DRO is therefore an acceptable variation in all the OPO configurations discussed herein.

The surfaces of mirrors 12 and 16 may be flat, concave or convex, as would be apparent to a person of ordinary skill. In the preferred embodiment, flat surfaces are advantageous for converting multimode pump radiation, because mode matching would then be dominated by the pump beam 50, rather than the OPO cavity. Efficiency reduction due to higher order transverse modes is not as severe in this case. Since the resonator mode of a plane parallel OPO consists of a beam of parallel light, a lens to focus the pump beam is also not required, thereby resulting in further simplification of the overall OPO laser design. Alternatives using concave-convex surfaces are possible, but are somewhat more complex to align, as a lens would then have to be provided to match the waist of the pump to the small waist of the OPO resonator mode, further requiring a single transverse-mode pump to assure high OPO efficiency. Mode matching is an important consideration in this type of configuration since any mode mismatch will cause a reduction in gain for optical parametric oscillation and a subsequent increase in threshold. In the preferred embodiment, a less complex and cheaper pump laser would provide a multi-mode beam, with the limits on allowed divergence dictated by the needs of the delivery system rather than the OPO.

The pump laser 20 consists generally of a neodymium-doped laser rod, such as Nd:YAG, pumped by either flashlamps or diode arrays. Both flashlamp and diode

pumped lasers of the required energy, peak power and repetition rate are well known and commercially available. Other appropriate laser media include crystals such as Nd:YLF, Nd:glass and Nd:YAlO$_3$, all of which provide the fundamental radiation at wavelengths falling in the range covered by the present application.

The crystal 15 preferably comprises a nonlinear material having high nonlinear coefficient, reasonably wide angular and temperature bandwidths, high damage threshold and minimal absorption at the idler or signal wavelengths. Ideally, a crystal that can be phase-matched non-critically would be preferred, since that would result in the largest possible walk-off angles allowing laser beams with even poor beam quality to be readily converted in long crystals. In a non-critical phase matching (NCPM) arrangement, the crystal is oriented such that phase matching is achieved along a propagation direction parallel to one of the crystal's principal axes (X, Y, or Z). In practice, it may not be possible with currently available materials and lasers to fulfill this criteria for a given application. Alternatively, a crystal with critical phase matching (CPM) may be acceptable as long as the walk-off angles and angular bandwidths are sufficiently high to allow efficient conversion of beams that are not necessarily single transverse mode. We have determined that the crystal known as Potassium Titanyl Phosphate (KTiOPO$_4$ or "KTP") is capable of fulfilling the requirements of this application, even though KTP could not be non-critically phase matched with the idler wavelengths of choice generated under pumping with a 1.06 μm laser. The KTP crystal is also known to exhibit some absorption at or near 3 microns, usually attributed to the presence of residual OH$^-$ radicals inherent to the growth process. Such absorption, if overly large, would seem to hinder the use of KTP for higher repetition rate applications.

We have determined, however, that under the right conditions, KTP is suitable as an OPO crystal for the corneal sculpting application, even with the level of absorption present with current material growth capability. As discussed below, this has

been achieved by the fortuitous combination of KTP's large temperature bandwidth and modest energy output and average power requirements of the surgical applications contemplated. With a crystal cut for Type-II phase matching, internal angles of 68 to 70 degrees would provide the required wavelengths for the idler when pumped by a 1.064 μm Nd:YAG laser, based on known material parameters for x-cut material. These angles may be sufficiently close enough to 90° to provide acceptance angles large enough to accommodate multi-mode pump beams with divergence exceeding many times the diffraction limit, if required. It is to be understood, however, that a judicious selection of components is necessary to achieve the operational conditions required of the surgical laser instrument, especially when the criterion of a compact, simple device consistent with portability in the field is factored in. Measured against the stringent parameters imposed by, for example, the corneal sculpting application, the particular combinations of various OPO elements and parameters using available materials and optics in the simple optical arrangement depicted in Figure 1 was not apriori obvious.

Accordingly, in one key aspect of this invention, a KTP crystal of sufficient length must be selected to allow efficient conversion of the 1 micron radiation. In a preferred embodiment, crystal lengths of at least 20 mm but potentially as long as 30 mm are appropriate, based on trade-offs of the walk-off angles that are realizable in a 68 to 70° Type-II CPM configuration for the x-cut crystal and estimates of the OPO gain required to produce idler output energy levels in the desired 5 to 30 mJ range. At this orientation, the acceptance angle for KTP is on the order of 5 cm-mrad, which is still large enough to accommodate the multi-mode pump preferred for the present application.

It is also to be understood that the specific wavelength of the output beam 52 can be altered by rotating the crystal with respect to the principal axes. This is a potentially useful feature in the surgical context since absorption properties may differ among different types of tissues and, for example, even within the same tissue, as a

function of temperature. Hence, a slight variation of wavelength could allow matching to the optimal absorption desired for a given procedure, thus enlarging the scope and utility of the OPO laser source. The limitation on the wavelength range that can be so obtained is determined by the relative sizes of the pump beam and the crystal aperture. Based on known parameters of KTP and the crystal sizes that are readily available, a wavelength range extending from 2.75 to just over 3 μm can all be covered with the present configuration, using any one of several commercially available neodymium-doped pump lasers.

Yet another important aspect of the invention relates to utilization of sufficiently short pump laser pulses such that OPO thresholds may be reached even with an unfocused pump beam arrangement. By eliminating the need for focusing the beam into the crystal, multimode or unstable resonator pump beam spatial distributions may be utilized, which has the advantage of significantly relaxing the requirements for a pump laser while alleviating difficulties associated with the OPO mode matching. In the preferred embodiment, pump pulse durations (FWHM) between 5 ns and 12 ns were found to be acceptable, producing efficient conversion to the idler's wavelengths of over 10% even for a multimode pump beam with divergence greater than 8 times the diffraction limit.

In another feature of the invention, bare crystal faces (i.e., non-anti-reflection (AR) coated) could be used to alleviate risk of damage associated with deficiencies of current coating technologies, whereby residual absorption near the 3 micron wavelength of choice can lower damage thresholds to impractical levels especially when short-duration pulses are utilized. Should high quality, 3 micron coatings become available for KTP, they could be used to advantage as this would lower the OPO losses and allow further reduction in the threshold for parametric oscillation for the same slope efficiency. It should be pointed out, however, that for optimal performance and damage-

free operation, the threshold should be such that the desired idler energy output is achieved with an input energy of no more than 3-4 times the threshold. By AR-coating the crystal, the reflectivity of the output coupler can be decreased, thereby dropping the circulating 2.9 µm power for the same output energy.

In the example quoted above, it was determined that with a bare crystal, damage to either the crystal or the optics could be avoided even with input pump energies in excess of 250 mJ for a 10 Hz beam, using all standard optics. Again, the ability to use unfocused beams with diameters on the order of 1 to 5 mm is considered a critical aspect in achieving this performance. To further suppress the potential for damage, especially on the input mirror which is subjected to the full pump power, other arrangements can be employed whereby the pump beam is not coupled through the same 0° input mirror that must also provide high reflection at 3 microns. There are indications that reflecting the 3 micron idler beam at 45° instead can increase the damage threshold when the best available 1 micron coatings are used.

Referring now to Figure 2, an alternative embodiment is illustrated, in which an "L-shaped" cavity is employed using the three mirrors indicated as 16, 17 and 18 to provide some separation between the path of the pump beam 50 and the idler beam 52. Thus, the pump is coupled through a 45° mirror 17 which is coated to also provide high reflection (at 45°) at the idler wavelengths. Mirror 18 is also coated to reflect the idler beam 52, but it is not subjected to the high power pump beam 50. The idler beam 52 is then coupled out through mirror 16, which is partially reflecting at the wavelength of the idler beam 52. Again, as in Figure 1, mirror 16 is preferably coated to provide back reflection of the pump beam 50, to lower the threshold for the parametric process. The advantage of this "L" cavity is that the fluence on the input mirror is reduced due to the 45° angle of incidence. Since this mirror 17 is typically the first component to damage, lower

fluence translates into reduced probability of damage to the OPO at a given level of energy output.

It is to be noted that in the embodiments of both Figures 1 and 2, the OPO axis must be slightly offset from the pump axis to prevent feedback into the pump laser 20. As an alternative, an isolator can be used between the pump laser and the OPO, although that would result in additional cost to the system. Figures 3 and 4 represent two alternative configurations that have no pump feedback as they rely on single-pass pumping. Thus, to increase conversion and reduce threshold, instead of back reflection of the pump into the same crystal, two OPO crystals are used in tandem. Figure 3 shows an arrangement whereby the pump beam 50 is coupled into the OPO cavity through a 45° mirror 11 that is coated for high reflection at the pump wavelengths and high transmission at the idler wavelengths. The pump beam passes through two nonlinear crystals 15' and 15" and is then transmitted out of the cavity through a mirror 12 that is coated for high transmission at the pump wavelength and high reflection at the 3.0 μm wavelength range of the idler beam 52. The idler beam 52 is coupled out of the cavity through a mirror 13 that is coated to partially reflect the idler wavelengths with the reflectivity selected to optimize the output from the cavity. In this singly resonant oscillator (SRO), each of the mirrors 11, 12 and 13 are coated to transmit the signal wavelength so that only the idler wavelength is resonant. An alternative arrangement would utilize a DRO which requires reflective coatings at the signal wavelength as well, and possibly also an additional beam splitter and/or other optics. The threshold would then be lower, but at a cost of increased complexity to the optics and in alignment procedures.

Figure 4 depicts a so-called "ring" configuration, where a prism 14 provides total internal reflection (TIR) of the beams in the cavity to thus pump two OPO crystals, marked again as 15 and 15' in a single pass arrangement. Two 45° mirrors 19 and 19' are coated to provide high transmission at the pump and signal wavelengths. Mirror 19' is also

coated to reflect the idler wavelength, while mirror 19 is partially reflective at 3 μm to outcouple the idler beam 52. As Figure 4 shows, the residual pump beam 50 is now exiting the OPO cavity via mirror 19', thus posing no feed-back problems. Also, since most of the signal beam 54 is transmitted out of the cavity also through mirror 19', there is less of a requirement for further attenuation of the signal in the path of the idler beam 52. While attractive on these last two counts, the configuration of Figure 4 is optically more complex, requiring additional elements as compared to the simple arrangement of Figure 1.

Figure 5 depicts substantially an alternative novel arrangement using a wave guide means 60 to couple the pump radiation into the OPO. In a preferred embodiment, the waveguide means comprises a hollow waveguide, a fiber or a fiber bundle. The advantages of using fiber delivery over an air path, fixed beam delivery system for a medical laser system are well known. They include easier alignment of the beam to the surgical site, more flexible adjustment of radiation, delivery angle and location, homogenization (or spatial smoothing) of a multimode beam and the ability to deliver radiation to internal locations not otherwise accessible. However, while fibers for transmitting 1 micron radiation are well developed with damage threshold that can withstand 100's of millijoules of short-pulse radiation, there are not similar fibers currently available to transmit short-pulse, 3 micron radiation. It would therefore be beneficial, if the higher power 1 micron pump beam could be transmitted over a fiber, allowing placement of the OPO in close proximity to the surgical microscope. Most of the advantages of a fiber delivery system would carry over when it is the pump light coupling through a fiber, with the exception of accessing internal locations. In particular, homogenization of the pump beam would result in a smoother profile for the output mid-IR beam, a highly desirable attribute in corneal ablation.

In the embodiment of Figure 5, the pump beam 50 is coupled through lenses 62 into a fiber 60, which may, in an alternative embodiment consist of a polarization

preserving fiber bundle or a hollow metal waveguide. A bundle may be suitable for accepting and transmitting a divergent pump beam 50 efficiently while allowing for collection and recollimation of light at the distal end through standard optical means 64. A lens 68, is shown as imaging the pump light into the OPO. In a preferred embodiment, the lens provides 1:1 imaging, assuming a 6 mm diameter bundle, to preserve the characteristics of the unfocused pump beam arrangement. Other aspect ratios are feasible, depending on the characteristics of available pump beams and fiber numerical apertures. In the preferred embodiment, the bundle may consist of a number of polarization preserving single mode fibers, as required to allow phase matching in the OPO crystal. Using this method, the damage limit of each fiber and the divergence of the beam(s) exiting the fiber(s) must be addressed, as would be apparent to a person of ordinary skill. In the case of the hollow metal waveguide, there are indications that polarization may be preserved and that a waveguide with approximately 1 mm diameter can deliver well over 100 mJ short pulse light at 1 μm wavelength. Such optical means as needed to correct residual depolarization of the pump light exiting waveguide 60, may be included as part of optical element 64 in the schematic of Figure 5. For simplicity, only the simple OPO configuration of Figure 1 is illustrated in Figure 5, but it is to be understood that any of the alternative OPO embodiments of Figures 2 through 4 can be used as the OPO element 10 in Figure 5.

It is to be noted that absorption in the KTP crystal of choice at or near 3 microns can limit scaling the repetition frequency of the OPO laser source of any of the configurations depicted above. Thus, absorption levels of 8-10% through the length of the crystal were found to be acceptable for the below 0.5 W average power OPO outputs considered this far, a result attributed to the unusually wide temperature bandwidth of KTP. However, it is recognized that to scale the repetition rate of the OPO to beyond 40-50 Hz may require some progress in the material area, whereby growth can be done under

altered conditions that do not favor formation of the absorbing OH⁻ ions. Such advances are currently contemplated, and should they be realized, would allow scaling the repetition rate to beyond the 50 Hz level. Additional scaling of the repetition frequency to the 100 Hz level can also be provided, for example, by interlacing the outputs of two OPOs, pumped by a single laser beam. These, as well as other arrangements utilizing a multiplicity of crystals, fall under the domain of the present invention.

Alternative KTP isomorphs such as KTA and RTA are also recognized as candidates for a mid-IR OPO laser using any one of the configurations specified above, given that they have similar properties to KTP. The selection of a particular crystal thus depends on a combination of characteristics, primarily related to favorable phase matching and minimal absorption at the wavelengths of choice for the present application.

Finally, there are a number of alternative OPO technologies that should they be developed in the near future could be used to advantage in the surgical OPO laser disclosed herein. Such improvements include use of a periodically-poled (PP) KTP which may provide drastically lower thresholds due to high nonlinearities. Output energies from a PP KTP are currently limited to less than 1 mJ due to small (<1 mm) apertures, but larger PP KTP crystals may become available through evolving technologies such as fusion bonding. Furthermore, in a periodically-poled form, $LiNbO_3$ pumped at 1 μm may also be a candidate crystal for producing the requisite 2.9-3.0 μm wavelengths under quasi phase-matching conditions which effectively simulate NCPM. Apertures are again limited to less than a mm, but future developments may result in larger PP crystals becoming available in the not too-distant future. Of course, absorption in $LiNBO_3$ at 3 micron remains a problem which will have to be addressed especially for higher repetitious rates.

We also note that utilization of a pump laser source with output wavelengths in the 0.85 to 0.9 μm range represents another alternative OPO configuration. With this pump wavelength, it is possible to non-critically phase-match KTP (x-cut), which

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would be highly beneficial to the surgical applications contemplated. Unfortunately, pump lasers providing such near-infrared radiation are not yet available as compact low cost, commercial lasers. Candidates include lamp-pumped Ti:sapphire and Cr:LiSAF, neither of which is readily available with the required energy (greater than 100 mJ), pulse duration (less than 25 ns), and repetition rate (greater than 10 Hz) capability. These or similar lasers may however be developed in the future and are thus included within the scope of this invention.

It is to be understood that the embodiments and variations shown and described herein are merely illustrative of the principles of this invention and that various modifications may be implemented by those skilled in the art without departing from the scope and spirit of the invention.

We claim:

1.   A mid-infrared laser system for performing a laser surgical procedure on a
tissue, said system comprising:

          a laser source means for producing a pump beam having a
wavelength ranging approximately from 1.0 to 1.1µm,

          a nonlinear crystal for parametrically converting the pump
beam into an idler beam and a signal beam, said idler beam having a
wavelength in the mid-infrared range corresponding approximately to an
absorption peak of said tissue; and

          means for directing said idler beam onto said tissue to
remove portions of said tissue primarily by a photo-mechanical ablation
process.

2.   The laser system according to claim 1, wherein said laser source means is a
neodymium-doped laser.

3.   The laser system according to claim 1, wherein said pump beam has a pulse
duration of less than 50 ns, and a repetition rate of at least 10 Hz and a transverse mode
structure consisting of single or multiple modes.

4.   The laser system according to claim 1, wherein said nonlinear crystal is a
Potassium Titanyl Phosphate (KTP) crystal.

5.   The laser system according to claim 1, wherein the nonlinear crystal is
rotatable about three principal axes.

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6.   The laser system according to claim 1, wherein said nonlinear crystal is made of a periodically poled non-linear material including KTP and isomorphs or $LiNbO_3$.

7.   The laser system according to claim 1, wherein said nonlinear crystal is tunable to optimize absorption in said tissue.

8.   The laser system according to claim 1, wherein said idler beam has energy output of at least 1 mJ.

9.   The laser system according to claim 1, wherein said idler beam achieves a thermal damage zone in corneal tissue of less than 2μm.

10.   The laser system according to claim 1, wherein said surgical procedure is a corneal ablation procedure.

11.   The laser system according to claim 10, wherein said corneal ablation procedure is a PRK technique based on a photospallation mechanism

12.   The laser system according to claim 1, wherein said directing means includes three mirrors comprising an "L shaped" arrangement.

13.   The laser system according to claim 1, wherein the nonlinear crystal is based on a doubly-resonant oscillator.

14.   The laser system according to claim 1, comprising a pair of said nonlinear crystals pumped by said laser source means with interlaced beams whereby an overall repetition rate of at least 20 Hz is achieved.

15.   The laser system according to claim 1, wherein the fluence onto the eye is between 100 mJ/cm^2 and 500 mJ/cm^2.

16.   A mid-infrared laser system for performing a laser surgical procedure on a tissue, said system comprising:

        a laser source means for producing a pump beam having a wavelength ranging approximately from 1.0 to 1.1μm,

        a nonlinear crystal for parametrically converting the pump beam into an idler beam and a signal beam, said idler beam having a wavelength in the mid-infrared range approximately between 2.85 and 3.0 μm; and

        means for directing said idler beam onto said tissue to remove portions of said tissue primarily by a photo-mechanical ablation process.

17.   A method for performing a laser surgical procedure on a tissue, said method comprising the steps of:

        generating a pump beam having a wavelength ranging approximately from 1.0 to 1.1μm,

        passing said pump beam through a nonlinear crystal to parametrically convert the pump beam into an idler beam and a signal beam,

said idler beam having a wavelength in the mid-infrared range corresponding approximately to an absorption peak of said tissue; and

directing said idler beam onto said tissue to remove portions of said tissue primarily by a photo-mechanical ablation process.

18.   The method according to claim 17, wherein said laser source means is a neodymium-doped laser.

19.   The method according to claim 17, wherein said pump beam has a pulse duration of less than 50 ns, a repetition rate of at least 10 Hz and a transverse mode structure consisting of single or multiple modes.

20.   The method according to claim 17, wherein said nonlinear crystal is a Potassium Titanyl Phosphate (KTP) crystal.

21.   The method according to claim 17, wherein the nonlinear crystal is rotatable about three principal axes.

22.   The method according to claim 17, wherein said nonlinear crystal is made of a periodically poled non-linear material including KTP and isomorphs or $LiNbO_3$.

23.   The method according to claim 17, further comprising the step of tuning said nonlinear crystal to optimize absorption in said tissue.

24.   The method according to claim 17, wherein said idler beam has energy output of at least 1 mJ.

25.   The method according to claim 17, wherein said idler beam achieves a thermal damage zone in corneal tissue of less than 2μm.

26.   The method according to claim 17, wherein said surgical procedure is a corneal ablation procedure.

27.   The method according to claim 26, wherein said corneal ablation procedure is a PRK technique based on a photospallation mechanism

28.   The method according to claim 17, wherein said directing means includes three mirrors comprising an "L shaped" arrangement.

29.   The method according to claim 17, wherein the nonlinear crystal is based on a doubly-resonant oscillator.

30.   A mid-infrared laser system for performing a laser surgical procedure on a tissue, said system comprising:

        a laser source for producing a pump beam having a wavelength ranging from approximately 0.85 to 0.9 μm;

        a nonlinear crystal rotatable about three principal axes for parametrically converting the pump beam into an idler beam and a signal beam, said idler beam having a wavelength in the mid-infrared range approximately between 2.85 and 3.0μm, wherein said nonlinear crystal is noncritically phase matched and said crystal is oriented such that phase matching is achieved along a propagation direction of said idler beam parallel to one of said principal axes; and

means for directing said idler beam onto said tissue.

31.   A mid-infrared laser system for performing a laser surgical procedure on a tissue, said system comprising:

        a laser source for producing a pump beam having a wavelength ranging from approximately 0.85 to 1.1μm, said pump beam having a defined polarization;

        a nonlinear crystal for parametrically converting the pump beam into an idler beam and a signal beam, said idler beam having a wavelength in the mid-infrared range between approximately 2.85 and 3.0μm;

        fiber means for coupling said laser source to said nonlinear crystal, said fiber means maintaining said polarization; and

        means for directing said idler beam onto said tissue to remove portions of said tissue primarily by a photo-mechanical ablation process.

32.   A method for removing corneal tissue from an eye of a patient, said method comprising the steps of:

        generating a pump beam having a wavelength of approximately 1 μm;

        passing said pump beam through a nonlinear crystal to parametrically convert the pump beam into an idler beam and a signal beam, said idler beam having a wavelength in the mid-infrared range corresponding to a corneal absorption peak; and

        scanning said beam across an area of said corneal tissue in a predefined pattern to remove portions of said corneal tissue primarily by a photo-mechanical ablation process.

33.   The method according to claim 32, wherein said laser source means is a neodymium-doped laser.

34.   The method according to claim 32, wherein said pump beam has a pulse duration of less than 50 ns, and a repetition rate of at least 10 Hz and a transverse mode structure consisting of single or multiple modes.

35.   The method according to claim 32, wherein said nonlinear crystal is a Potassium Titanyl Phosphate (KTP) crystal.

36.   The method according to claim 32, wherein the nonlinear crystal is rotatable about three principal axes.

37.   The method according to claim 32, wherein said nonlinear crystal is made of a periodically poled non-linear material including KTP and isomorphs or $LiNbO_3$.

38.   The method according to claim 32, further comprising the step of tuning said nonlinear crystal to optimize absorption in said tissue.

39.   The method according to claim 32, wherein said idler beam has energy output of at least 1 mJ.

40.   The method according to claim 32, wherein said idler beam achieves a thermal damage zone in corneal tissue of less than 2μm.

41.   The method according to claim 32, wherein said surgical procedure is a corneal ablation procedure.

42.   The method according to claim 41, wherein said corneal ablation procedure
is a PRK technique based on a photospallation mechanism

43.   The method according to claim 32, wherein said directing means includes
three mirrors comprising an "L shaped" arrangement.

44.   The method according to claim 32, wherein the nonlinear crystal is based on
a doubly-resonant oscillator.

45.   A mid-infrared laser system for removing corneal tissue from an eye of a
patient, said system comprising;

        a laser source means for producing a pulsed pump beam
having a wavelength ranging approximately from 1.0 to 1.1μm;

        a nonlinear crystal for parametrically converting the pump
beam into an idler beam and a signal beam, said idler beam having a
wavelength in the mid-infrared range corresponding approximately to a
corneal absorption peak; and

        means for directing said idler beam onto said eye in a
predefined pattern to remove portions of said corneal tissue primarily by a
photo-mechanical ablation process.

46.   The laser system according to claim 45, wherein said laser source means is a
neodymium-doped laser.

47.   The laser system according to claim 45, wherein said pump beam has a pulse duration of up to 50 ns, and a repetition rate of at least 10 Hz and a transverse mode structure consisting of single or multiple modes.

48.   The laser system according to claim 45, wherein said nonlinear crystal is a Potassium Titanyl Phosphate (KTP) crystal.

49.   The laser system according to claim 45, wherein the nonlinear crystal is rotatable about three principal axes.

50.   The laser system according to claim 45, wherein said nonlinear crystal is made of a periodically poled non-linear material including KTP and isomorphs or $LiNbO_3$.

51.   The laser system according to claim 45, wherein said nonlinear crystal is tunable to optimize absorption in said tissue.

52.   The laser system according to claim 45, wherein said idler beam has energy output of at least 1 mJ.

53.   The laser system according to claim 45, wherein said idler beam achieves a thermal damage zone in corneal tissue of less than 2μm.

54.   The laser system according to claim 45, wherein said surgical procedure is a corneal ablation procedure.

55.   The laser system according to claim 54, wherein said corneal ablation procedure is a PRK technique based on a photospallation mechanism

56.   The laser system according to claim 45, wherein said directing means includes three mirrors comprising an "L shaped" arrangement.

57.   The laser system according to claim 45, wherein the nonlinear crystal is based on a doubly-resonant oscillator.

58.   The laser system according to claim 45, comprising a pair of said nonlinear crystals pumped by said laser source means with interlaced beams whereby an overall repetition rate of at least 20 Hz is achieved.

59.   The laser system according to claim 45, wherein the fluence onto the eye is between 100 mJ/cm^2 and 500 mJ/cm^2.

ABSTRACT

A laser parametric generator for surgical applications is disclosed which utilizes short-pulse, mid-infrared radiation. The mid-infrared radiation may be produced by a pump laser source, such as a neodymium-doped laser, which is parametrically down-converted in a suitable nonlinear crystal to the desired mid-infrared range. The short pulses reduce unwanted thermal effects and changes in adjacent tissue to potentially sub-micron levels. The parametrically converted radiation source preferably produces pulse durations shorter than 25 ns at or near 3.0 μm but preferably close to the water absorption maximum associated with the tissue. The down-conversion to the desired mid-infrared wavelength is preferably produced by a nonlinear crystal such as KTP or its isomorphs. In one embodiment, a non-critically phased-matched crystal is utilized to shift the wavelength from a near-infrared laser source emitting at or around 880 to 900 nm to the desired 2.9-to-3.0 μm wavelength range. A fiber, fiber bundle or another waveguide means utilized to separate the pump laser from the optical parametric oscillation (OPO) cavity is also included as part of the invention.
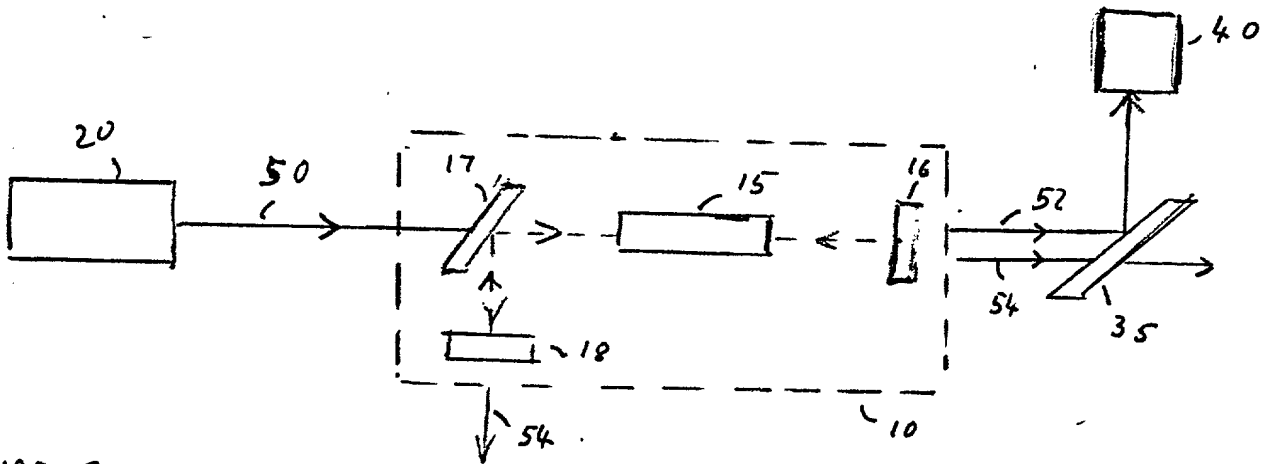
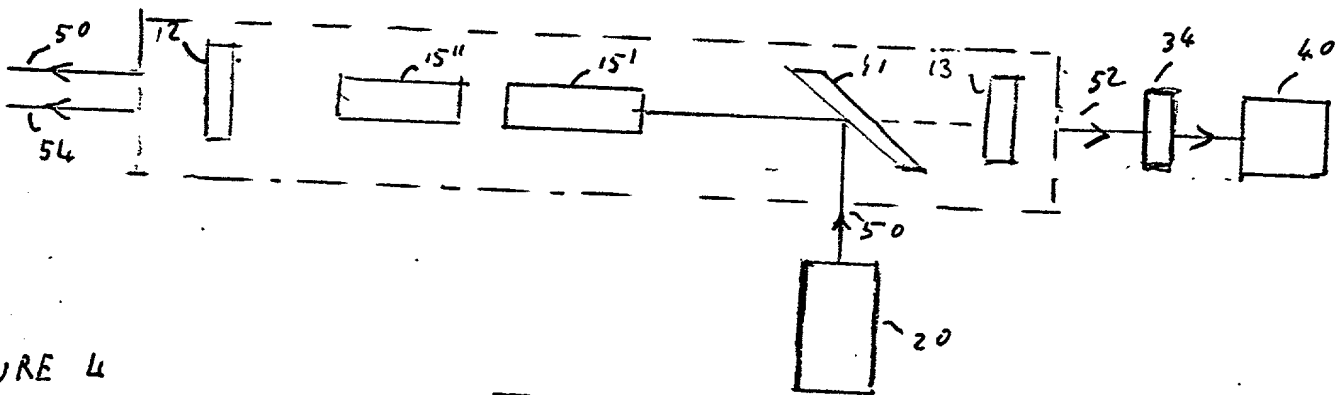S2885731.DOC 03/14/97
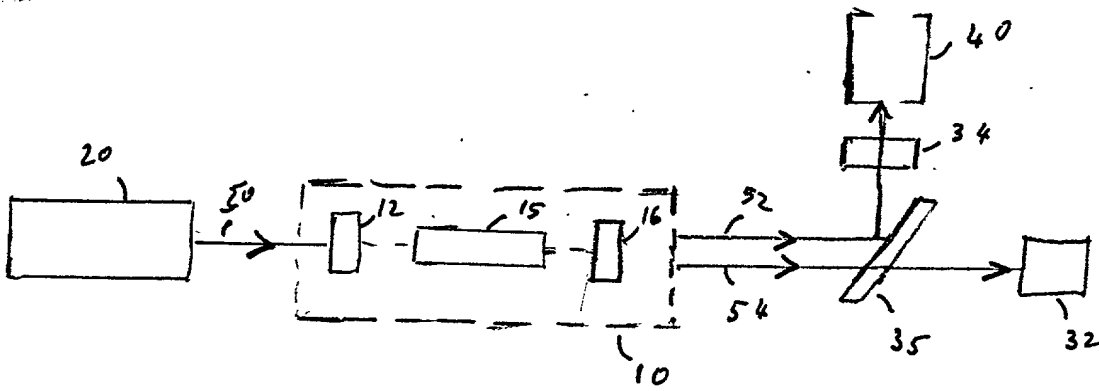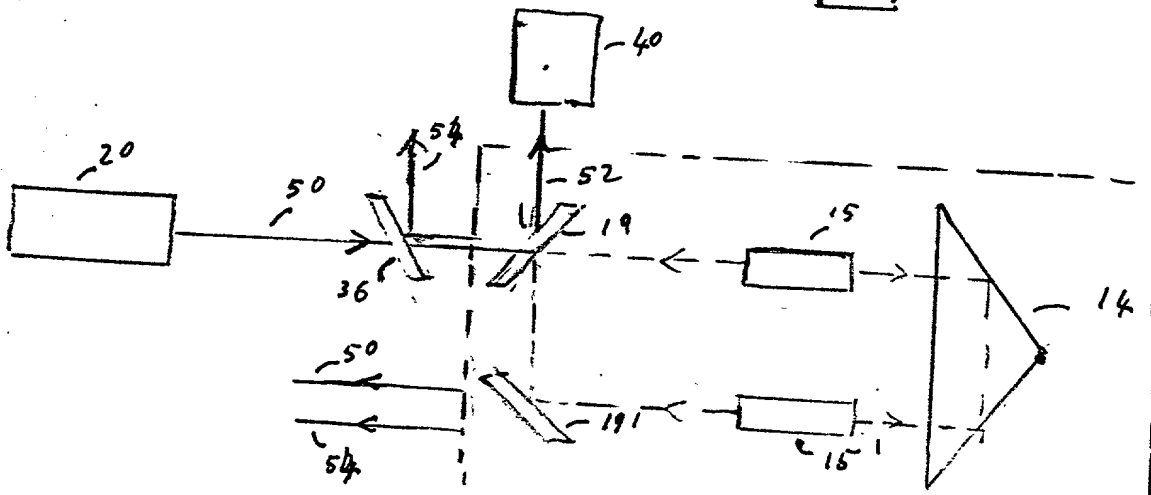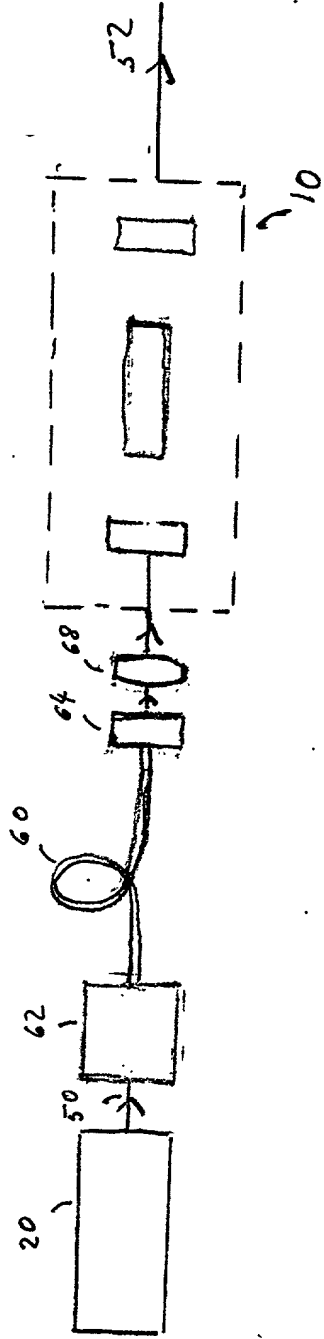
FIGURE 2

FIGURE 3

FIGURE 4

FIGURE 5

Declaration, Power of Attorney, and Petition

As a below named inventor, I/we hereby declare that:

My/Our residence, post office address and citizenship is/are as stated below next to my/our name(s),

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled: SHORT PULSE MID-INFRARED PARAMETRIC GENERATOR FOR SURGERY, the specification of which *(check one)*

    ☐   is attached hereto; or

    ☒   was filed on March 14, 1997 as Application Serial No. 08/816,097 and was amended on
_____ (if applicable); or ·

<div align="center">PCT FILED APPLICATION ENTERING NATIONAL STAGE</div>

    ☐   was described and claimed in International Application No. _____ filed on
_____ and as amended on _____ (if applicable).

    I/We hereby state that I/we have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above, and that it contains a full, clear, concise and exact description of the subject matter for which a patent is sought.

    I/we acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, § 1.56(a).

    ☐ (Check if applicable) I/We hereby claim foreign priority benefits under Title 35, United States Code § 119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

<div align="center">

Prior Foreign Application(s)

</div>

			Priority Claimed?	
			☐ Yes	☐ No
(Number)	(Country)	Day/month/year filed		
			☐ Yes	☐ No
(Number)	(Country)	Day/month/year filed		

    ☒ (Check if applicable) I/We hereby claim the benefit under Title 35, United States Code, § 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, § 112, I/we acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, § 1.56(a) which occurred between the filing date of the prior application and the national or PCT international filing date of this application:

08/549,385	October 27, 1995	Pending
(Application Serial No.)	(Filing Date)	Status (Patented, pending, abandoned)
(Application Serial No.)	(Filing Date)	Status (Patented, pending, abandoned)

    ☐ (Check if applicable) I/We hereby authorize the U.S. attorneys or agents named herein to accept and follow instructions from _____ as to any action to be taken in the Patent and Trademark Office regarding this application without direct communication between the U.S. attorneys or agents named herein and myself/ourselves. In the event of a change, I/we will notify in writing the U.S. attorney or agent named herein.

☐ (Check if applicable) In this continuation-in-part application, insofar as the subject matter of any of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, Section 112, I acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, Section 1.56(a) which occurred between the filing date of the prior application and the national or PCT international filing date of this application.

I/We hereby declare that all statements made herein of my/our own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.
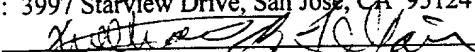
I/we hereby appoint:

Allen D. Brufsky, Reg. No. 21,056
Barry Kramer, Reg. No. 20,622
Michael P. Dilworth, Reg. No. 37,311
Scott D. Wofsy, Reg. No. 35,413
Immac J. Thampoe, Reg. No. 36,322

of the firm of CUMMINGS & LOCKWOOD, whose address is Four Stamford Plaza, P.O. Box 120, Stamford, Connecticut 06904-0120, as my/our attorneys with full power of substitution and revocation, to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith.
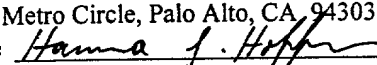
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Telephone Calls should be directed to Barry Kramer, by dialing (203) 351-4522.

Wherefore I/we pray that Letters Patent be granted to me/us for the invention or discovery described and claimed in the foregoing specification and claims, and I/we hereby subscribe my name to the foregoing specification and claims, declaration, power of attorney, and this petition.

Full name of sole or first inventor: William B. TELFAIR
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Inventor's signature _____ Date __6/10/97__

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Second Inventor's signature _____ Date __6/11/97__

☒ (Check if applicable) ATTACHED IS ADDED PAGE TO DECLARATION, POWER OF ATTORNEY, AND PETITION FOR SIGNATURE BY THIRD AND SUBSEQUENT INVENTORS.

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Added Page to
Declaration, Power of Attorney, and Petition
for Signature by Third and Subsequent Inventors

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Fourth Inventor's signature _____ Date 6/25/97

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Third Inventor's signature _____ Date 6/16/97

Full name of fifth joint inventor, if any _____
Residence _____
Citizenship _____
Post Office Address_____
Fifth Inventor's signature _____ Date _____

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